NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

September 3, 2009

MATERIALS LABORATORY FACTUAL REPORT Report No. 09-060

A. ACCIDENT

Place	:	Charlestown, West Virginia
Date	:	July 13, 2009
Vehicle	:	Boeing 737-300, N387SW
Operator	:	Southwest Airlines, Flight 2294
NTSB No.	:	DCA09FA065
Investigator	:	Bob Benzon (AS-10)

B. COMPONENTS EXAMINED

Fuselage Skin Assembly between BS 827 and 847 and Stringer 1 and 2L

C. DETAILS OF THE ANALYSIS

While at 34,000 feet Southwest Airlines flight 2294, a Boeing 737-300 registration N387SW[1], experienced a rapid depressurization and diverted to Charleston, West Virginia. At the time the aircraft had accumulated 50,883 hours of service and 42,569 cycles. Upon inspection at Charleston, a three sided hole was discovered in the crown of the aircraft fuselage near the leading edge of the vertical stabilizer, as shown in figure 1 (A). The hole measured approximately 17.4 inches longitudinally and between 11.5 and 8.6 circumferentially. The hole was formed in skin assembly part number 65C35792-3. The skin assembly extended across the crown of the fuselage from stringer 4[2] on the left side of the aircraft (S-4L) to stringer 4 on the right side (S-4R). Longitudinally the skin assembly extended from body station[3] (BS) 727 aft to body station 908.

A portion of the skin surrounding the hole was excised from the aircraft and examined in the NTSB materials laboratory. Representatives from The Boeing Company, Southwest Airlines, the FAA and the Southwest Airlines Pilot Association were present from July 21 thru July 23, 2009 during the initial examination. Additional examinations occurred at The Boeing Company under NTSB direction.

[1] N387SW is serial number 26602, Boeing line number 2627, variable number PS772, basic number P6354 manufactured in June, 1994.
[2] Stringers are numbered from the top centerline of the fuselage, designated stringer 1, and down the right and left sides of the fuselage (when viewed from the rear) and designated L or R to denote the appropriate side.
[3] Body stations are numbered from the front of the aircraft rearward and correspond to inch measurements along the fuselage.

The removed skin section, shown in figure 2, extended from approximately BS 825.5 to BS 849 and from about 2 inches below S-2L to 2 inches above S-1. The three sided hole was formed by a 13.2 long longitudinal crack at the upper (top) edge and a curving 14.75 long roughly circumferential crack at the forward edge and another curving 8.5 long circumferential crack at the aft edge. The drawing in figure 3 illustrates the location and dimensions of the hole. The material below the longitudinal crack and between the circumferential cracks was deformed outward and folded downward and aft forming a flap in the skin. The forward circumferential portion of the crack crossed stringer 2L and the flap area of the skin was disbonded from the corresponding area of the underlying doubler along the S-2L land. Local deformations in the skin indicated that several rivets at S-2L were also pulled through the skin in the disbonded area indicating out of plane loading between the skin and stringer in this area. The aft circumferential portion of the crack crossed a portion of the tear strap at BS 847 and disbonded from the doubler. Initial optical inspection did not uncover any evidence of corrosion or preexisting mechanical damage on the surfaces of either the skin or the doubler.

Skin assembly, p/n 65C35792-3, is composed of a -4 outer sheet (the skin, covering the entire assembly), and a -49 waffle pattern doubler hot bonded to the inner surface. Both pieces were specified as 0.036 inch thick, 2024 –T3 clad[4] aluminum sheet per Federal Specification QQ-A-250/5[5]. Boeing reports that the assembly is manufactured by forming and bonding two full sheets together then selectively masking and chemical milling (chem mill) away pockets of the doubler sheet to form a waffle pattern. The drawing in figure 3 shows the hole in relation to the waffle pattern milled into the doubler (shown as dashed lines). The wide circumferential areas of the doubler are referred to as tear strips and the narrower longitudinal areas are referenced as stringer lands where the skin stringers are riveted. For the -3 skin assembly the area immediately adjacent to the hole location is not milled to provide for possible installation of an emergency locator transponder antenna.

Close optical examinations of the fracture surfaces on the piece of skin section uncovered some small areas of post separation mechanical damage on the mating fracture surfaces but otherwise they appeared mostly in good condition. Further magnified inspections of the fracture surface revealed bright faceted surfaces indicative of fatigue progress at the inner surface of the skin. The circumferential crack regions displayed matte grey slant fracture surfaces bulk deformation patterns indicative of overstress tearing away from the longitudinal portion of the crack.

As indicated in figure 4 (a), the longitudinal portion of the skin crack was in line with and followed the chem milled edge of the adjacent doubler. High magnification viewing along the longitudinal crack revealed continuous fatigue thumbnails (shiny faceted areas) propagating outward (thru-the-thickness) from multiple origins at the inner surface of the skin. The longitudinal crack length that displayed fatigue was 13.7 inches long from approximately BS 831 to BS 844. The visual depth of the fatigue regions, see figure 4 (b) varied along the crack length. Visually near the middle of the longitudinal crack, the fatigue crack appeared to completely penetrate the skin thickness for a distance of approximately 3 inches, between BS 835 and BS 838. Forward and aft of this region the crack surfaces outboard of the fatigue had a matte gray coloration typical of overstress separation. The extent of penetration generally lessened with distance fore and aft of this location. To

[4] Thin layers of pure aluminum are clad onto high strength aluminum for enhanced corrosion resistance.
[5] QQ-A-250/5 Aluminum Alloy 2024, Plate and Sheet.

access the depth of fatigue penetration, measurements were made at 50X approximately every inch along the longitudinal crack. Deformation and damage at the outer surface of the skin made accurate measurement difficult and the actual location of the outer surface was estimated in most instances. Table A (following) presents the nominal fatigue depth as a percentage of the estimated skin thickness.

Table A. Nominal Fatigue Depth vs Location

Station	Percent Fatigue
BS 831	16.2%
BS 832	17.0%
BS 833	20.1%
BS 834	28.1%
BS 835	31.5%
BS 835.5	35.3%
BS 836.5	100.0%
BS 838	23.4%
BS 839	27.2%
BS 840	29.4%
BS 841	16.8%
BS 842	19.6%
BS 843	14.6%
BS 844	13.4%

A section was cut from the upper crack face that included the apparent thru thickness fatigue region (about BS 834.5 to BS 839), cleaned in acetone, and examined with a scanning electron microscope (SEM). SEM examinations clearly showed microscopic features typical of fatigue progression, including areas of striations, in the previously identified regions, as shown in figure 5. Oxidation was noted on the crack surfaces from approximately BS 835.8 to BS 837.1, consistent with exposure of the crack faces for some amount of time prior to the decompression. The area of thru thickness fatigue was reduced in size when ductile dimple formations were found intermingled with fatigue features (mixed mode cracking) in portions of the crack. Fatigue progression was found to completely penetrate the skin thickness along a 1.3 inch length of the crack (BS 835.8 to BS 837.1). Regions of fatigue and mixed mode cracking were found adjoining the thru the thickness fatigue region, as shown in figure 6. The mixed mode regions were found for approximately 0.8 inch forward (to BS 835) and 0.9 inch aft (to BS 838) of the thru the thickness fatigue region. Further forward and aft of these regions the crack showed thru-the-thickness fatigue partially through the skin with ductile dimple overstress thru the remaining thickness, as shown in figure 7. No indication of longitudinal or for/aft crack growth was observed. The drawing in figure 8 summarizes and illustrates these findings.

Measurements of fatigue striation spacing were conducted at four locations along the crack length, two at BS 836.5 and one each at BS 836.2 and BS 837.2. Of the two measurement locations at BS 836.5, one was made by Boeing on the upper crack face and

the other by the NTSB on the lower crack face, referenced 836.5 Boeing and 836.5 NTSB respectively. The measurements at BS 836.2 and BS 837.2 were both conducted by the NTSB on the lower crack face and are annotated as such. For the measurements, images of resolved striations were recorded along with their relative X-Y coordinates and that of the originating surface. The SEM stage and viewing was arranged such that the distance of the image from the origin surface was determined by the Y axis alone. Average striation spacing was then established over 4 to 20 consecutive stria in each field of view with appropriate corrections for viewing magnification. Figure 9 (a) shows the measurement locations for the striation count at BS 836.2 along with images 704 and 710 as typical striations measurement images. Striation spacing in each image were determined by both this investigator and a Boeing metallurgist, such that there were two sets of data generated at each location for 8 data sets. The data for these are presented in the four tables (B, C, D, and E) below.

Data are presented for striation spacing at BS 837.2, however it should be noted that this location was within the previously noted zone of mixed mode cracking. Striations and ductile dimples were interspersed in the later stages of progression and the striation spacing became comparatively large. Striations were also noted during examinations in the partial thickness fatigue regions; however there were insufficient data points with resolvable striations for inclusion.

Both the skin and doubler are specified as 0.036 inch thick, 2024-T3 Alclad sheets per QQ-A-250/5. Sheet thickness, chemistry and metallurgical structure were examined on a metallographic section cut thru both the skin and doubler near stringer 2L and BS 827. Thickness measurements[6] established the skin and doubler thicknesses as 0.036 and 0.035 inch respectively. The clad layers of the two sheets measured between 0.0016 and 0.0019 inch after etching the specimen with Keller's reagent. QQ-A-250/5 requires a nominal clad thickness of 5% of composite sheet thickness (0.0018 inch) per side with a minimum of 4% (0.0014 inch). No microstructural abnormalities were noted in either sheet. Energy dispersive x-ray spectra (EDS) from the core of the sheets detected aluminum, copper, magnesium and manganese in ratios consistent with 2024 aluminum alloy. Only aluminum was found in the clad layers consistent with alloy 1230 as specified by QQ-A-250/5.

Electrical conductivity measurements performed on the skin with the clad layer were within the typical range for 2024-T3 Alclad, 28.5 to 35.0 % IACS[7], as identified in MIL-H-6088[8].

Joe Epperson
Senior Metallurgist

[6] Performed on a calibrated Optical Gaging Products, Smartscope, an optically based computerized measurement tool.
[7] International Annealed Copper Standard.
[8] MIL-H-6088G, Military Specification, Heat Treatment of Aluminum

Table B Striation Count Data BS 836.5 Boeing						
NTSB count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
	0.000	0.00000				
24	0.133	0.00700	27450	9	0.524	2.12
29	0.309	0.01400	16140	8	0.856	6.63
30	0.473	0.02100	5260	8	0.640	15.2
32	0.531	0.02300	5290	9	0.778	16.3
31	0.621	0.02600	5460	8	1.043	23.9
33	0.726	0.03100	2192	9	0.783	39.7
Boeing count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
	0.000	0.00000				
24	0.133	0.00700	25,000	4	0.250	2.50
29	0.309	0.01400	15,000	7	0.750	7.14
30	0.473	0.02100	4,980	7	0.500	14.3
32	0.531	0.02300	5,000	7	0.750	21.4
31	0.621	0.02600	5,000	4	0.500	25.0
33	0.726	0.03100	2,000	7	0.750	53.6

da/dN calculated as Distance divided by Stria count result divided by Scaled Mag then divided by 1,000,000. Result in micro inches per cycle.

Example image 24 (0.524 in / 9)/ 27450 = 2.12E-06 in / cycle / 1,000,000 = 2.12 µin/cycle.

Table C Striation Count Data BS 836.5 NTSB						
NTSB count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
origin	39.858	0.00000				
654	39.953	0.00374	27750	8	0.772	3.48
656	40.051	0.00760	33950	6	0.449	2.20
655	40.055	0.00775	33950	8	0.570	2.10
653	40.156	0.01173	27750	12	1.450	4.35
651	40.258	0.01575	6900	9	0.730	11.8
657	40.384	0.02073	8180	9	1.600	21.7
658	40.440	0.02292	8180	10	1.500	18.3
Boeing count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
origin	39.858	0.00000				
654	39.953	0.00374	27750	8	0.772	3.48
655	40.055	0.00775	33950	8	0.570	2.10
653	40.156	0.01173	27750	12	1.450	4.35
651	40.258	0.01575	6900	9	0.730	11.8
657	40.384	0.02073	8180	9	1.600	21.7
658	40.440	0.02292	8180	10	1.500	18.3

Table D Striation Count Data BS 836.2 NTSB						
NTSB count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
origin	39.990	0.00000				
714	40.144	0.00604	40500	5	0.620	3.06
706	40.254	0.01038	11960	6	0.355	4.95
715	40.272	0.01109	27250	10	0.547	2.01
711	40.344	0.01393	19790	11	0.883	4.06
705	40.425	0.01712	16900	9	1.155	7.59
704	40.426	0.01717	21120	20	2.010	4.76
710	40.441	0.01777	13240	20	1.941	7.33
708	40.525	0.02106	13240	13	1.396	8.11
700	40.552	0.02213	7620	5	0.497	13.0
709	40.657	0.02625	6590	10	1.272	19.3
Boeing count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
origin	39.990	0.00000				
714	40.144	0.00604	40500	5	0.620	3.06
706	40.254	0.01038	13870	7	0.750	7.72
715	40.272	0.01109	20000	11	0.500	2.27
711	40.344	0.01393	15000	5	0.500	6.67
705	40.425	0.01712	20000	9	0.750	4.17
704	40.426	0.01717	25000	9	1.000	4.44
710	40.441	0.01777	10000	9	1.000	11.1
708	40.525	0.02106	10000	5	0.500	10.0
700	40.552	0.02213	8920	5	0.500	11.2
709	40.657	0.02625	5000	8	1.000	25.0

Table E Striation Count Data BS 837.2 NTSB						
NTSB Count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
Origin	45.193	0.00000				
569	45.578	0.01515	19750	6	0.683	5.76
568	45.582	0.01533	13490	8	0.693	6.42
567	45.677	0.01906	13440	9	0.693	5.73
566	45.738	0.02146	6760	15	1.199	11.8
565	45.802	0.02398	4085	8	1.090	33.4
564	45.843	0.02560	4085	8	1.271	38.9
562	45.848	0.02579	4085	5	0.616	30.2
563	45.916	0.02847	2493	5	1.201	96.3
Boeing Count						
Image	Y (mm)	Dist from origin (in)	Scaled Mag	Stria count	Distance (inch)	da/dN (µin/cycle)
Origin	45.193					
569	45.578	0.01515	19750	9	1.000	5.63
568	45.582	0.01533	13490	5	0.500	7.41
567	45.677	0.01906	13440	12	1.000	6.20
566	45.738	0.02146	6760	15	1.200	11.8
565	45.802	0.02398	4085	8	1.250	38.2
564	45.843	0.02560	4085	9	2.000	54.4
562	45.848	0.02579	4085	7	2.000	69.9
563	45.916	0.02847	2493	5	1.000	80.2

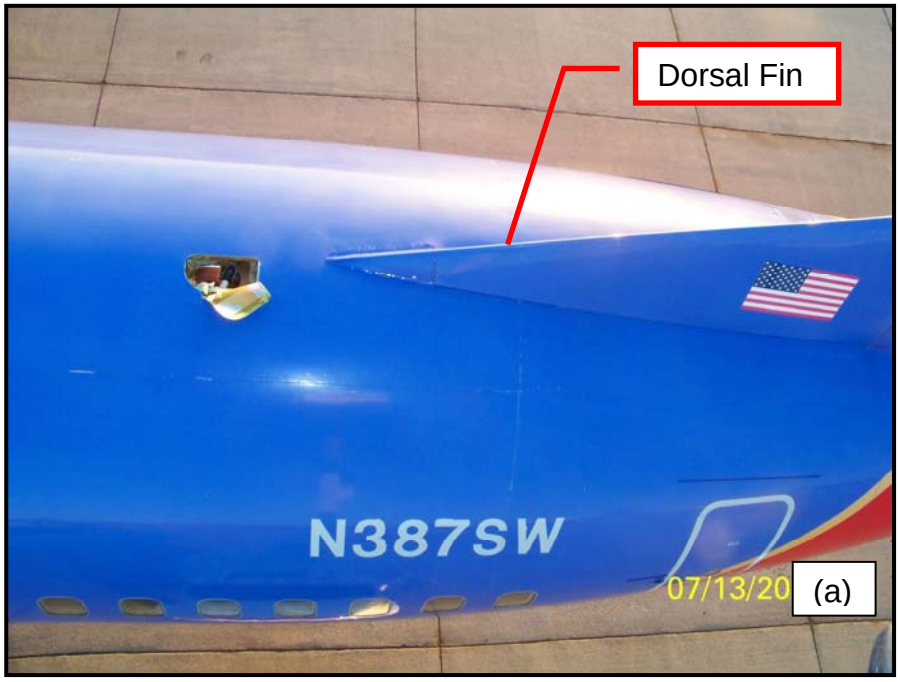
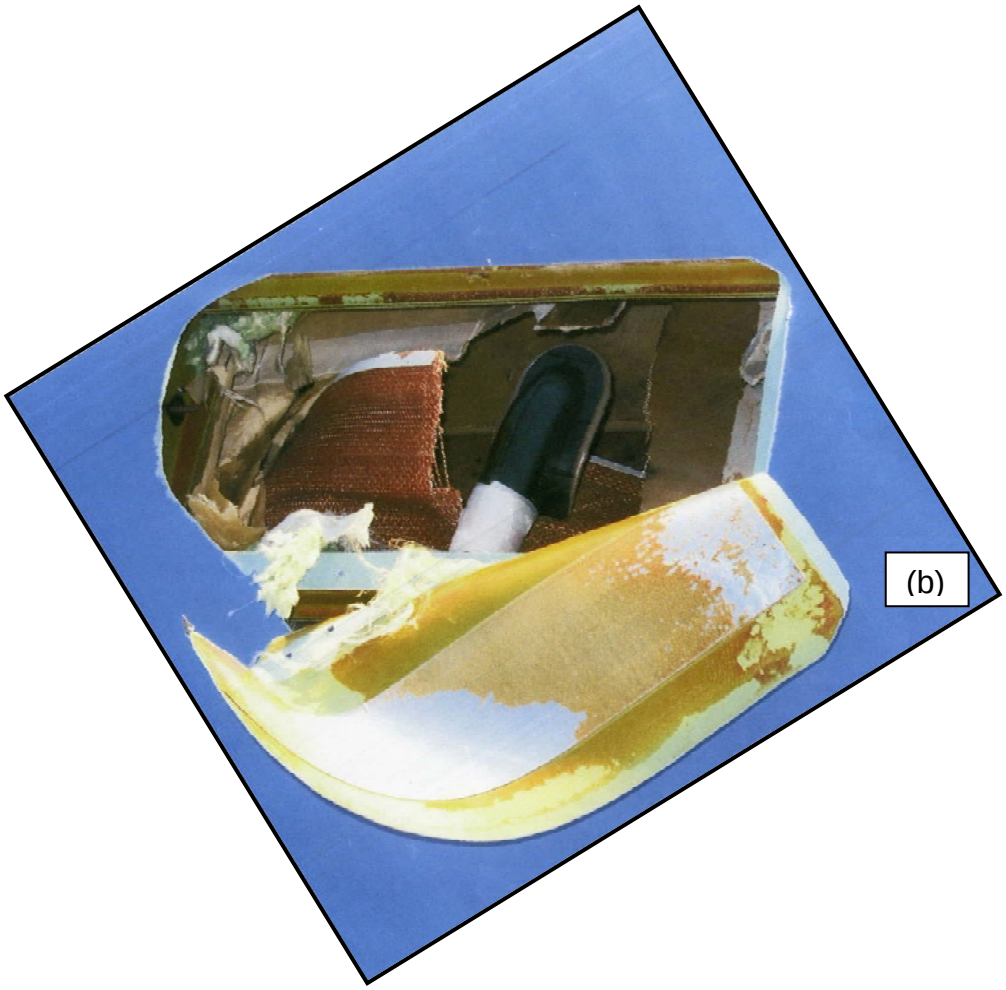


Figure 1—Overall view of the flap (a) showing its relationship to the vertical stabilizer. View (b) shows a closer view of the flap.



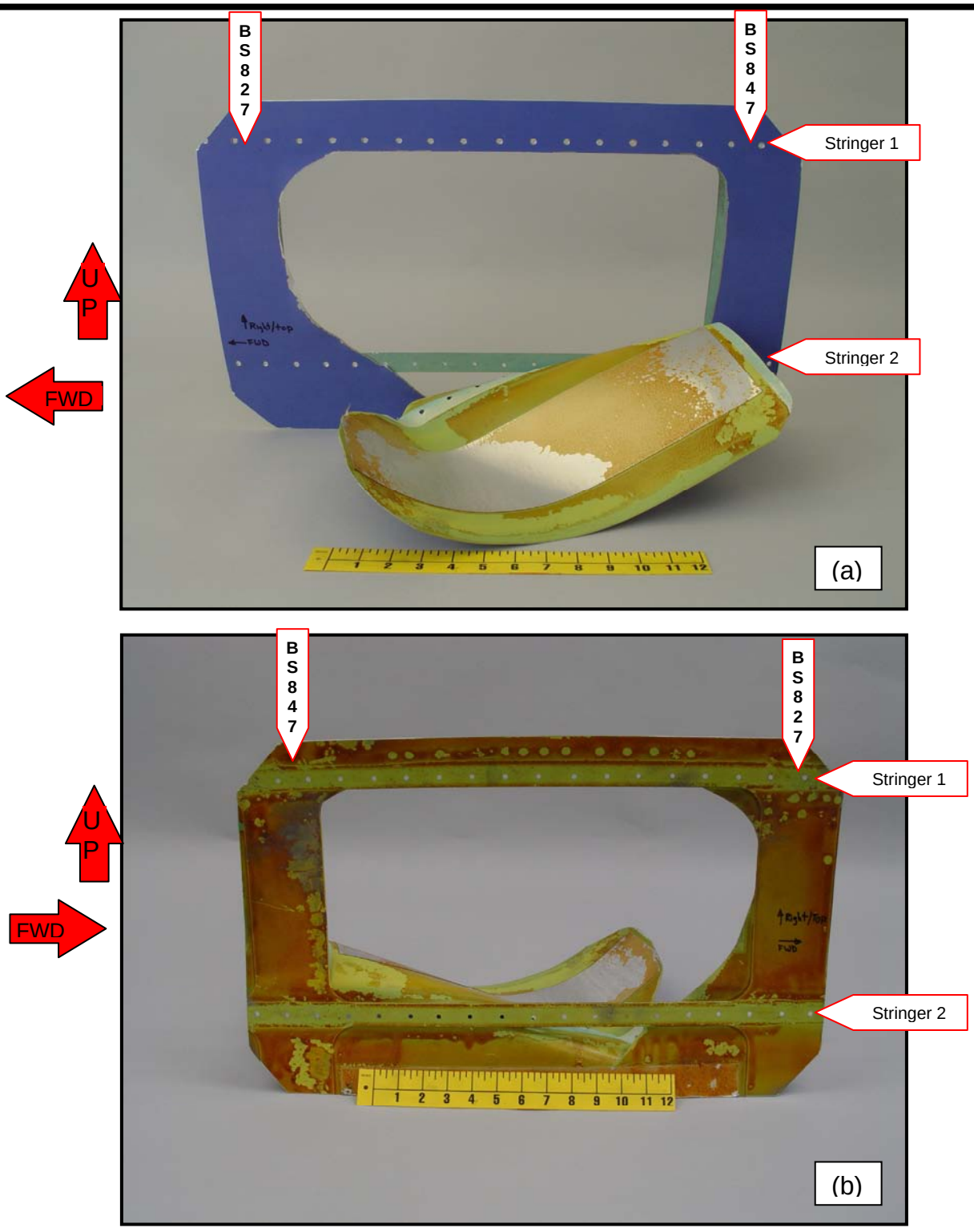
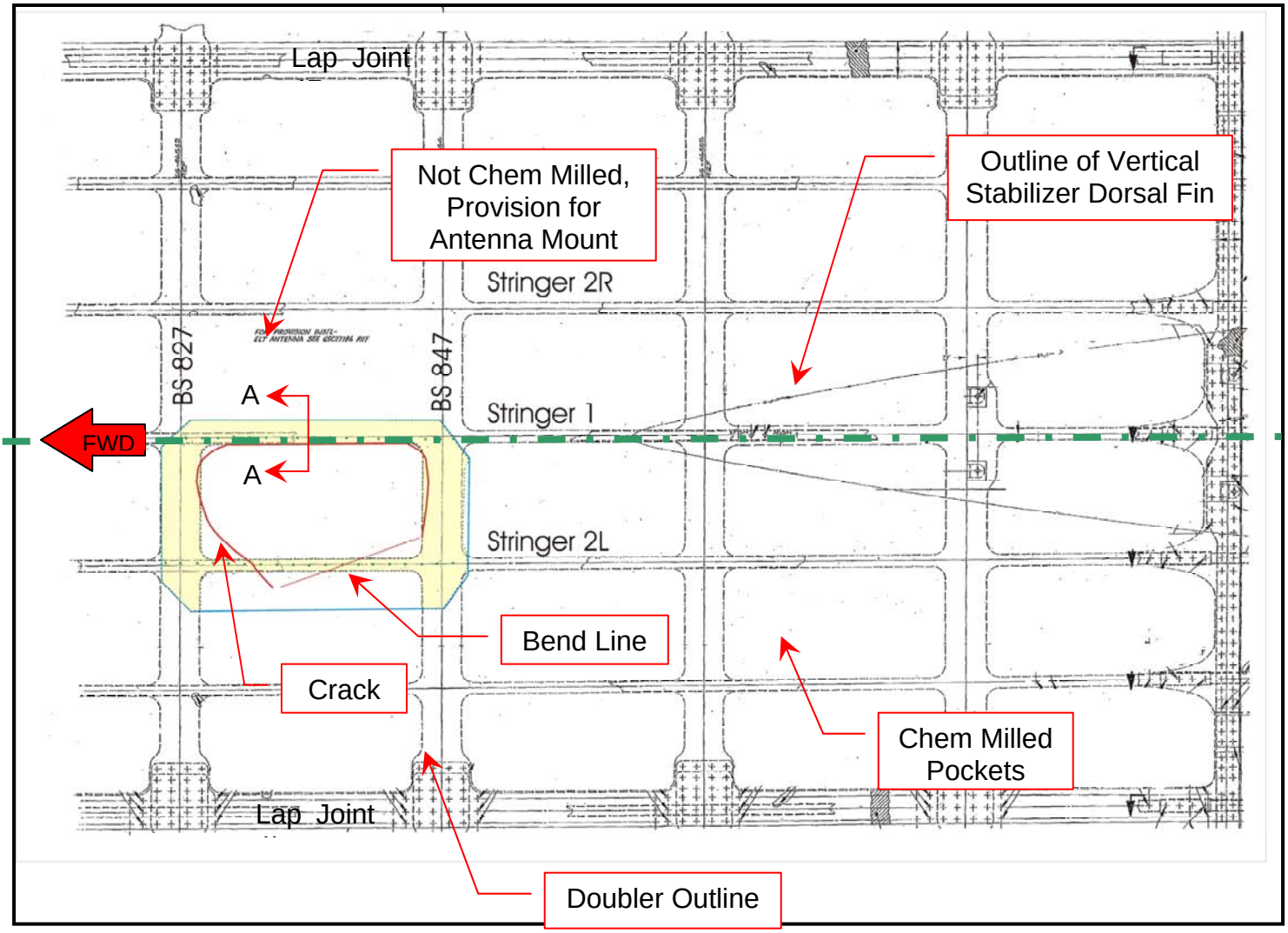


Figure 2—Exterior (a) and interior (b) views of the removed section of skin containing the crack and flap.



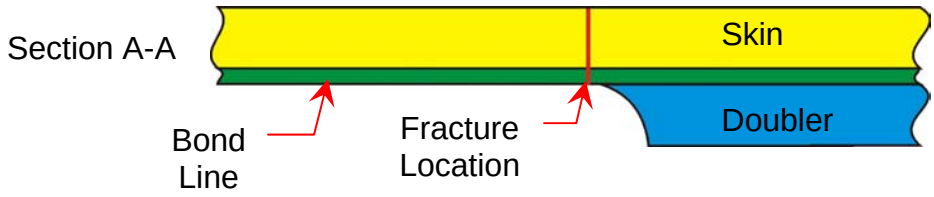
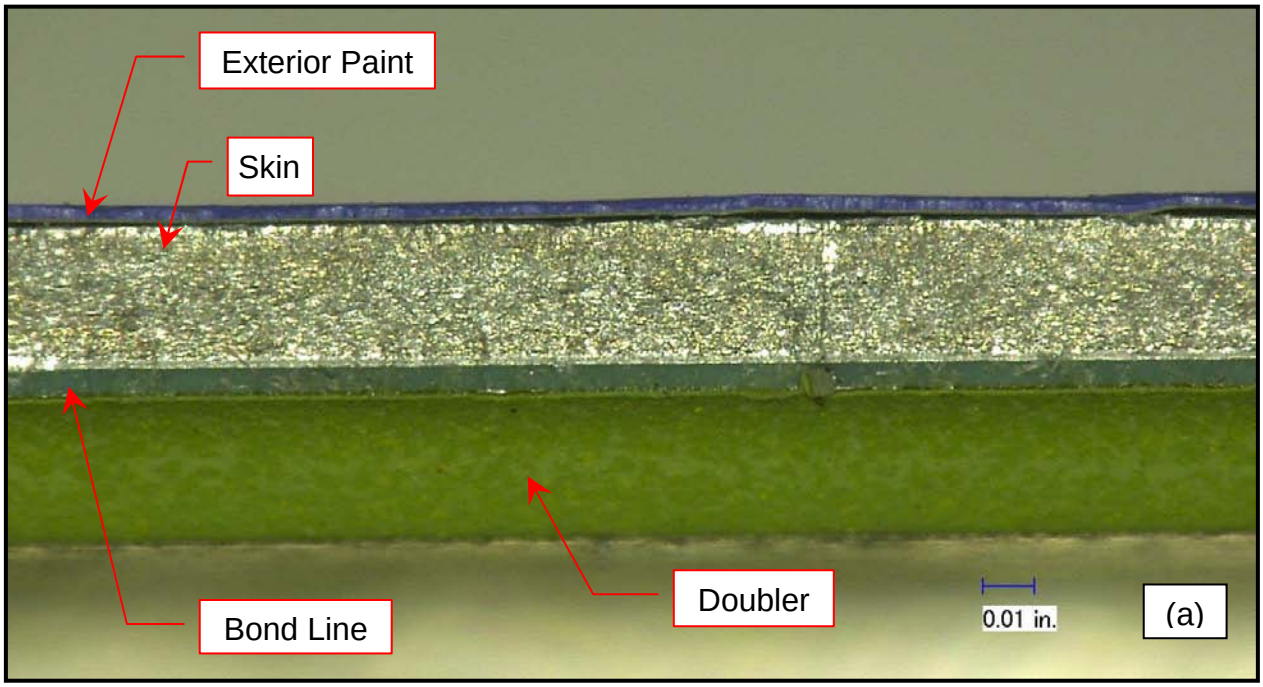


Figure 3—Illustration showing the location of the crack (red Line) and the removed section (outlined in blue) on the skin panel. Hidden lines denote the location and shape of the underlying doubler. Dashed green line located on the aircraft centerline. Section A-A show typical cross section at the fracture location.



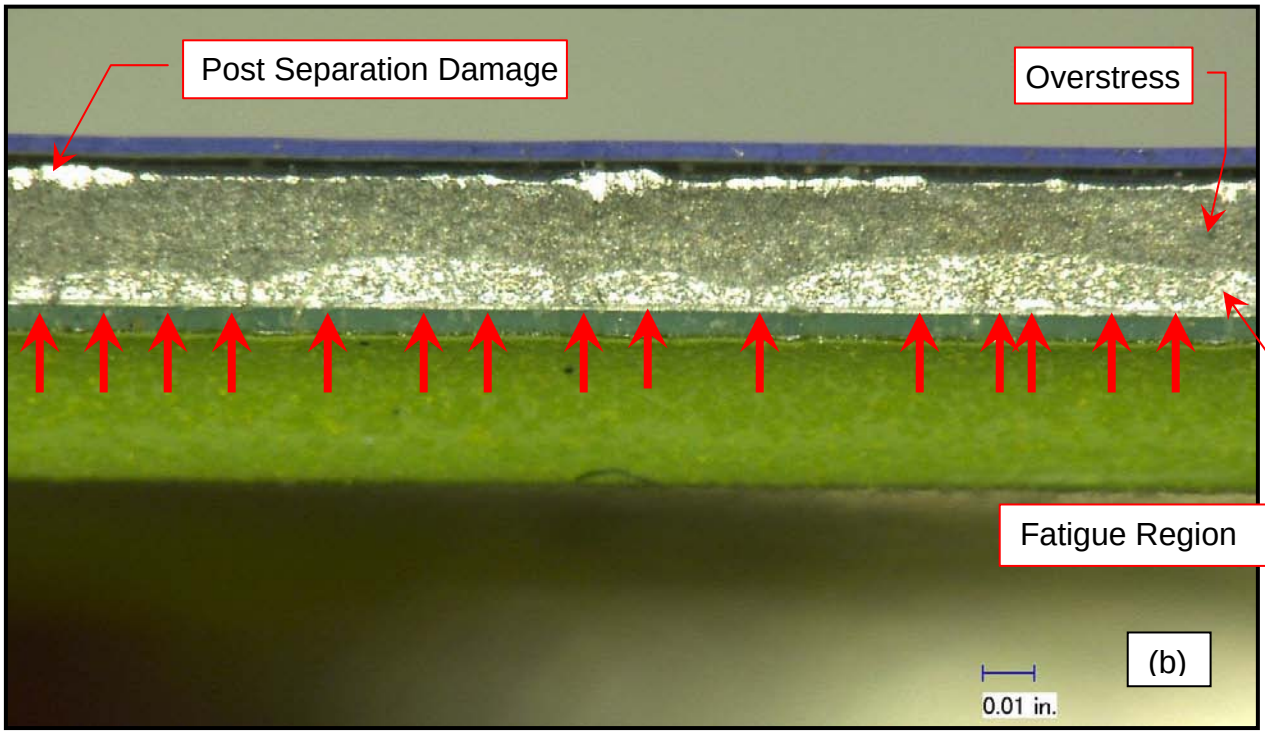
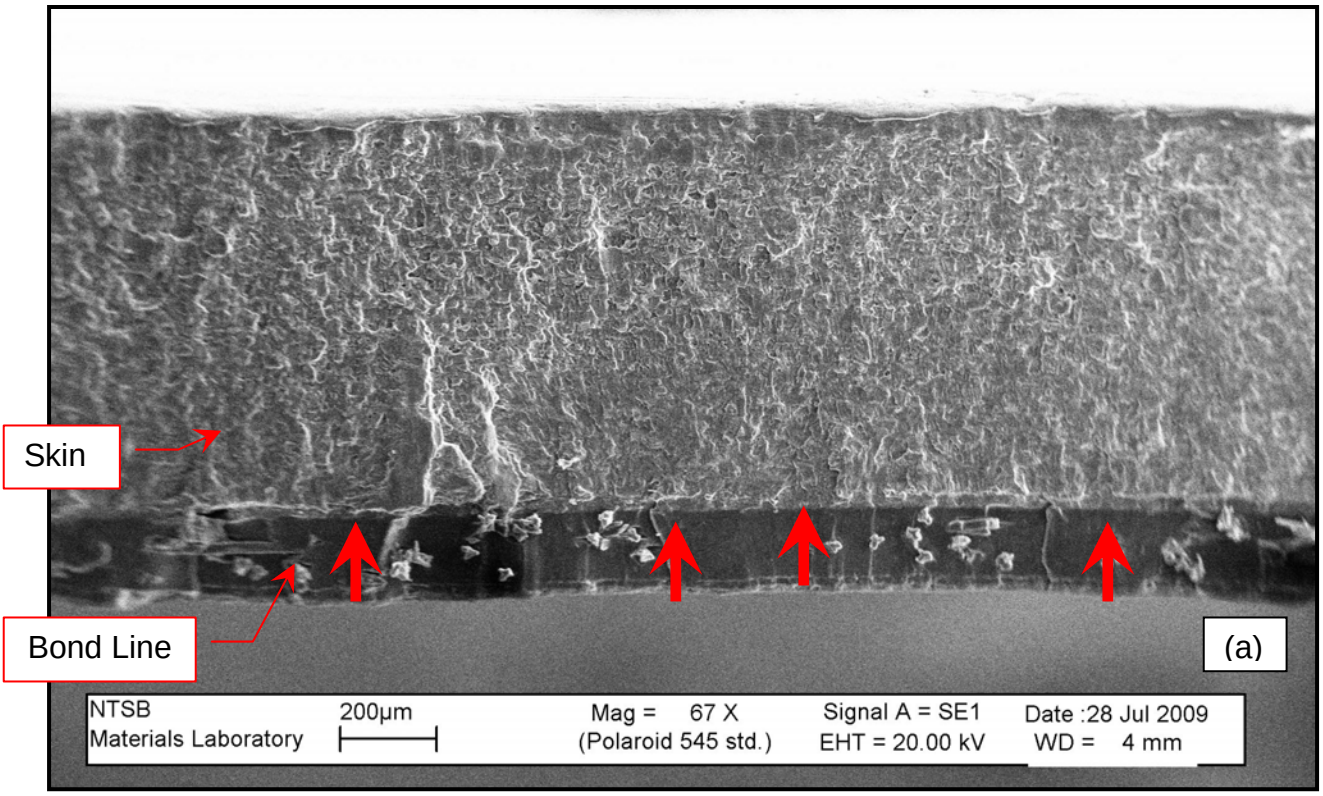
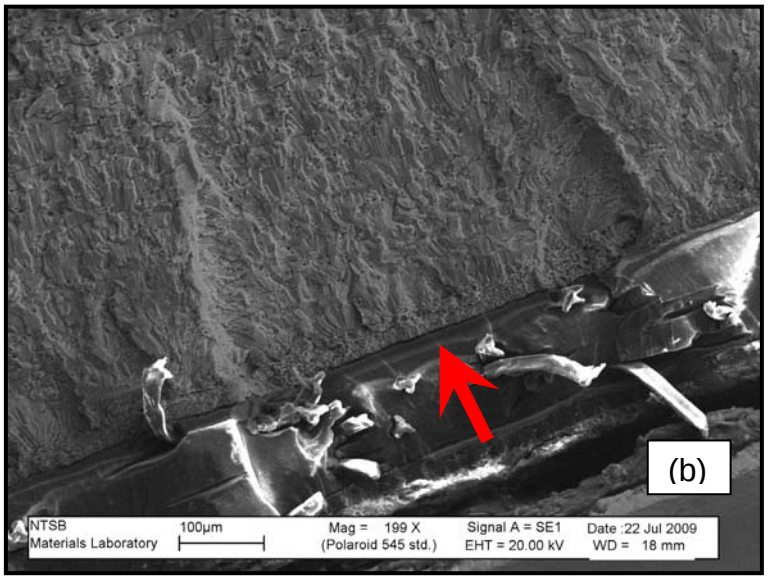


Figure 4—Higher magnification optical views of the longitudinal crack upper face. View (a) shows a portion of the thru-the-thickness fatigue area with the doubler and bond line also denoted. View (b) shows partial thickness fatigue (shiny regions) and overstress (dull gray). Red arrows in view (b) denote approximate origin locations on the interior surface of the skin.





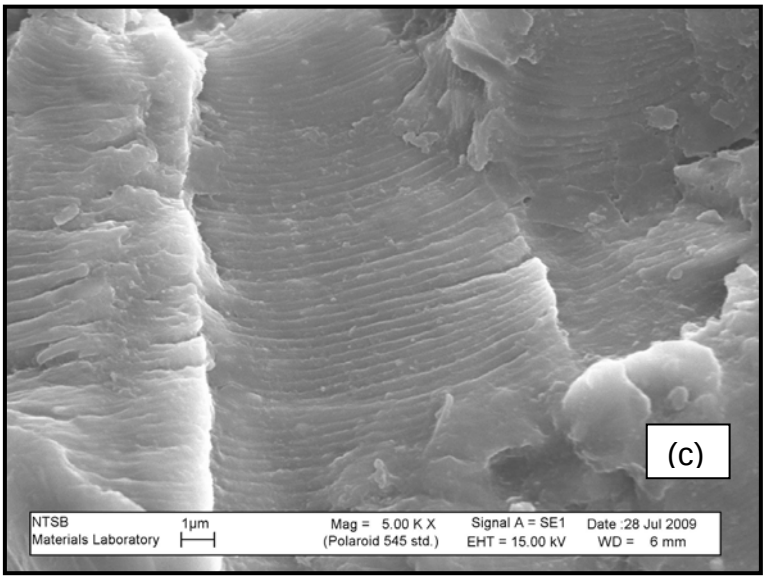


Figure 5—SEM views of typical areas of the thru-the-thickness fatigue region of the longitudinal crack. View (a) shows the full thickness of the skin with fatigue origins at red arrows. A closer view of an individual origin is displayed in view (b) and typical fatigue striations shown in view (c).

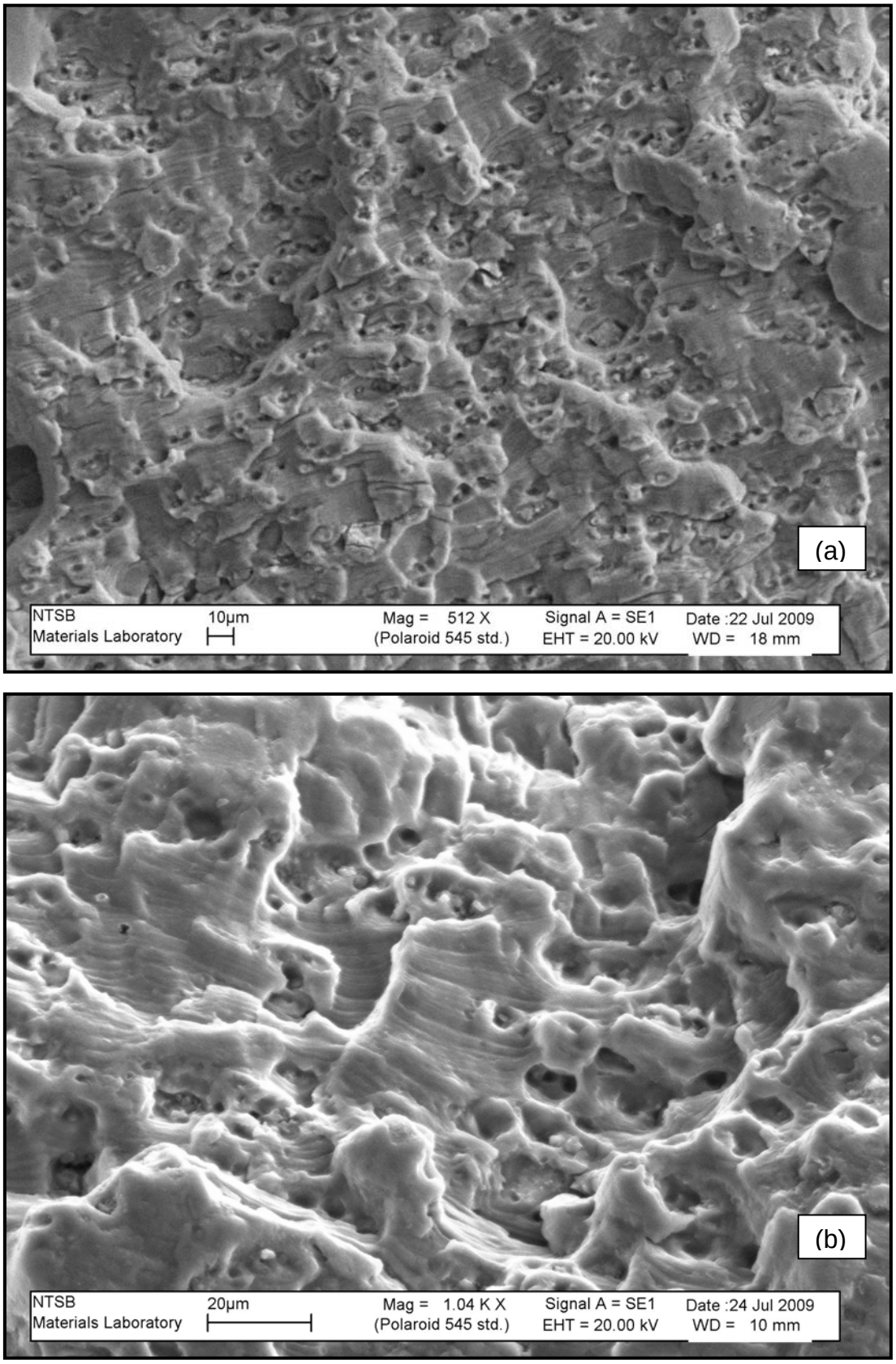


Figure 6—Two SEM views showing dimple rupture and fatigue striations within the mixed mode region.

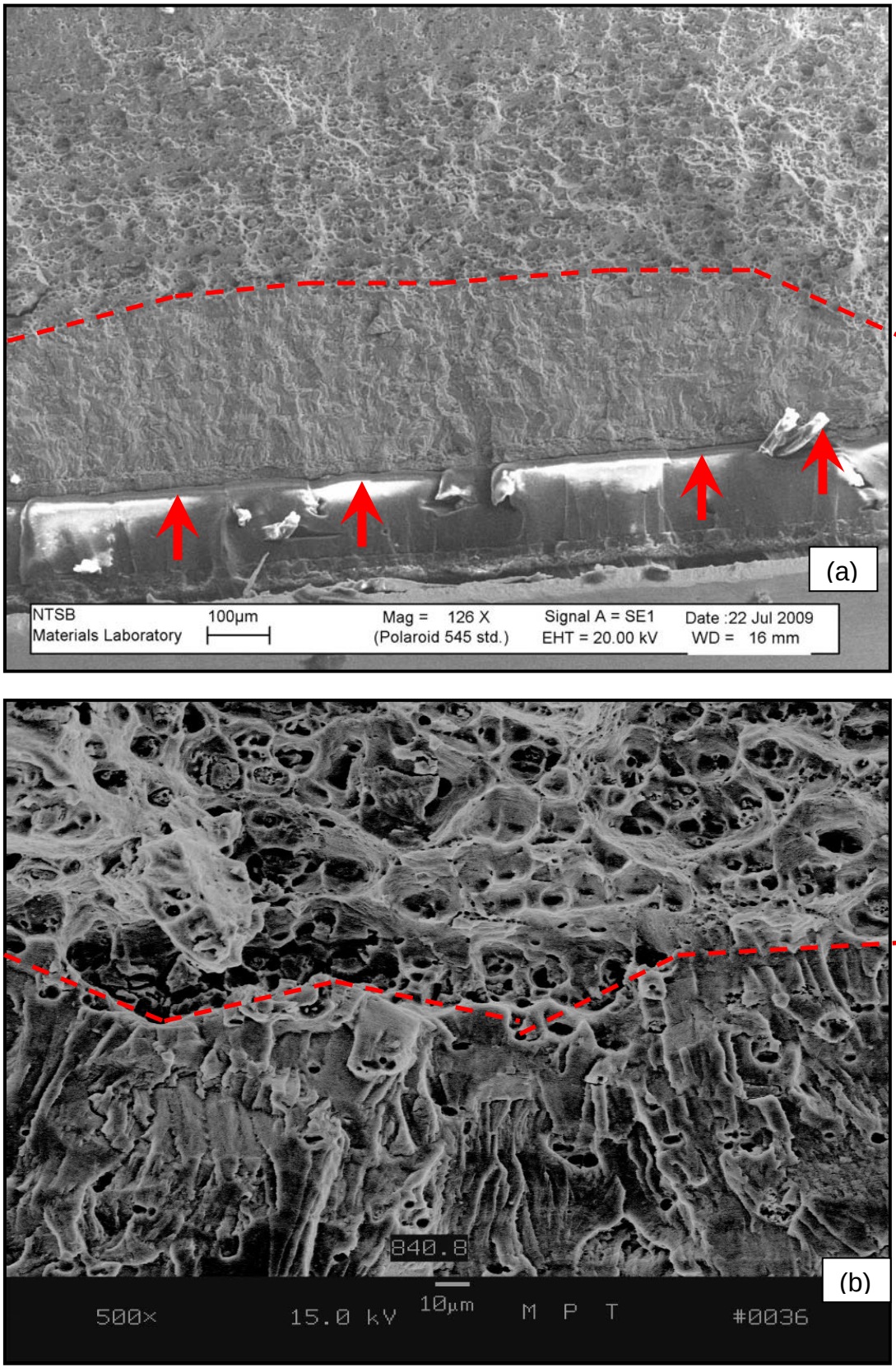
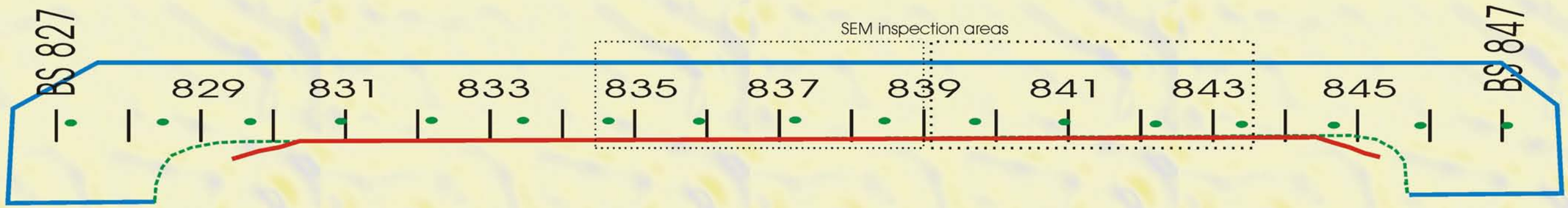
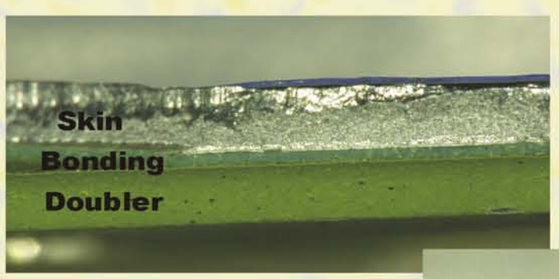
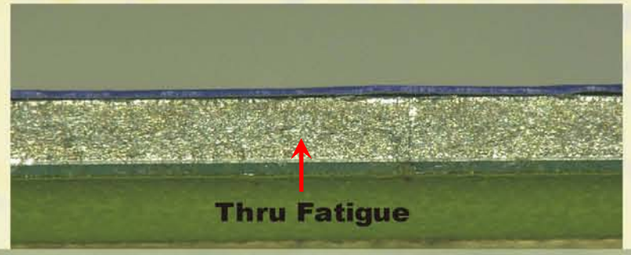
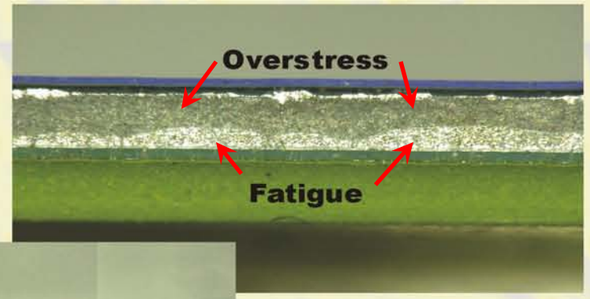


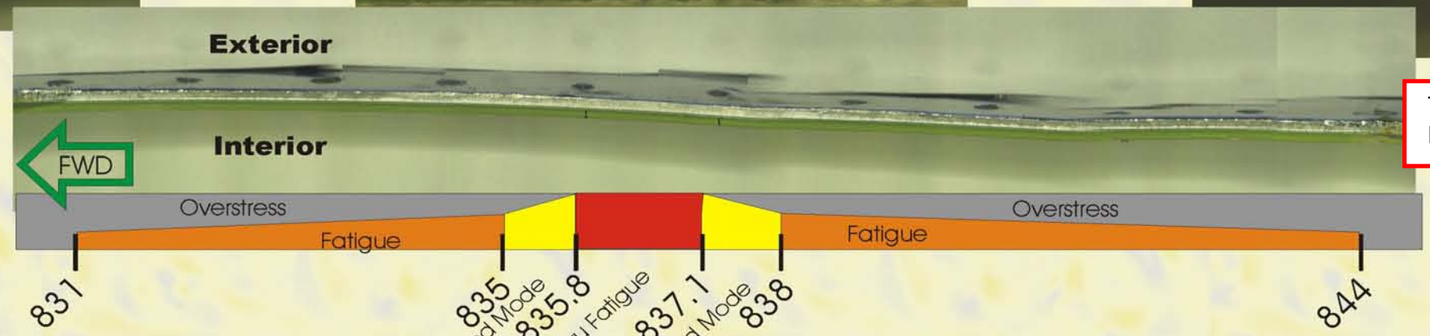
Figure 7—SEM views of a typical area of a partial penetration fatigue region. With fatigue adjacent to the interior skin surface (below dashed lines) and ductile dimple overstress thru the remainder of the skin thickness. View (b) is a closer view of the interface between the fatigue and overstress.





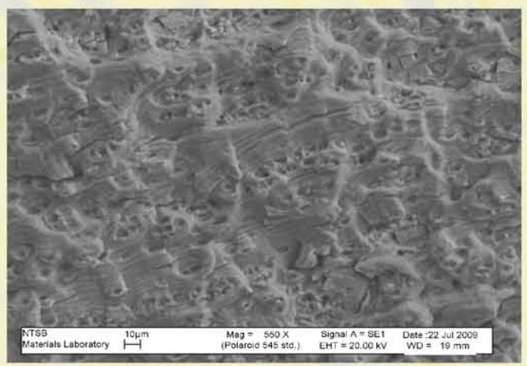




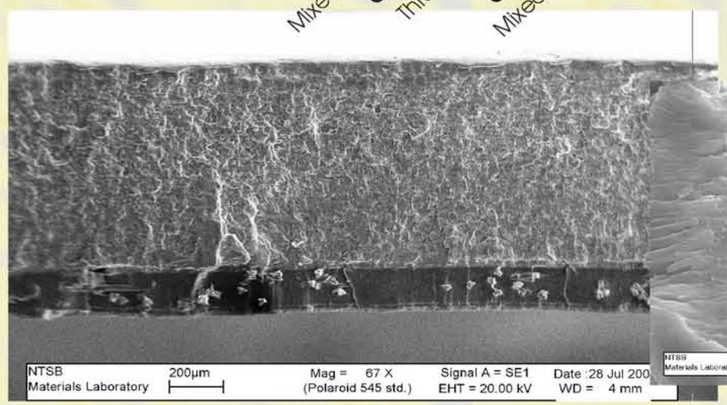


Thickness Expanded

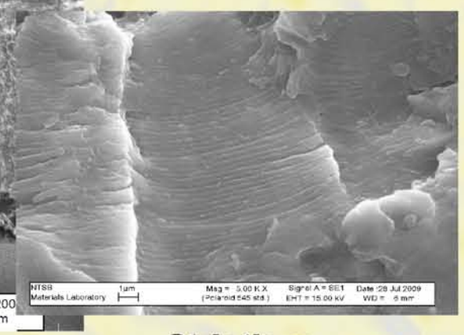
Figure 8--Montage showing the longitudinal crack face at center with a plan view illustration at top showing the crack location in relation to body stations. Drawing below crack face summarizes separation modes along the crack's length with their approximate body stations. Other views show typical features throughout the crack.



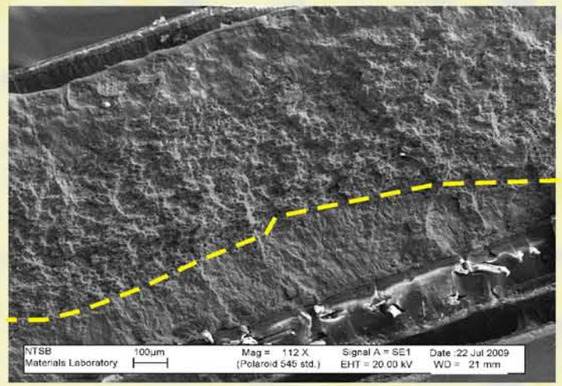
Mixed Mode



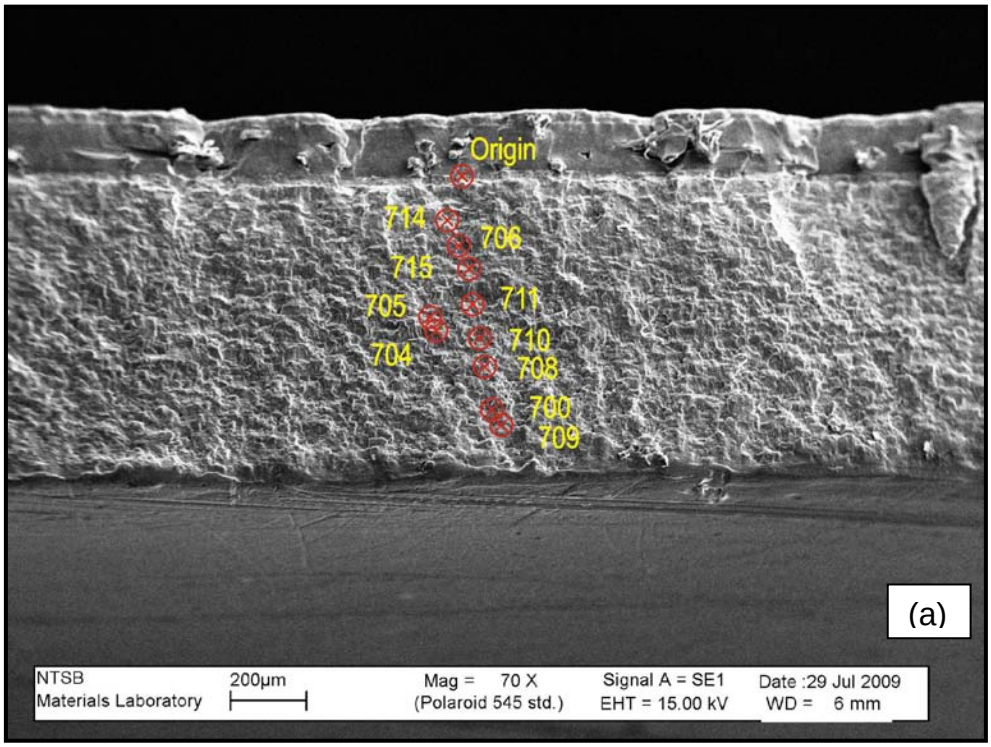
Thru Fatigue

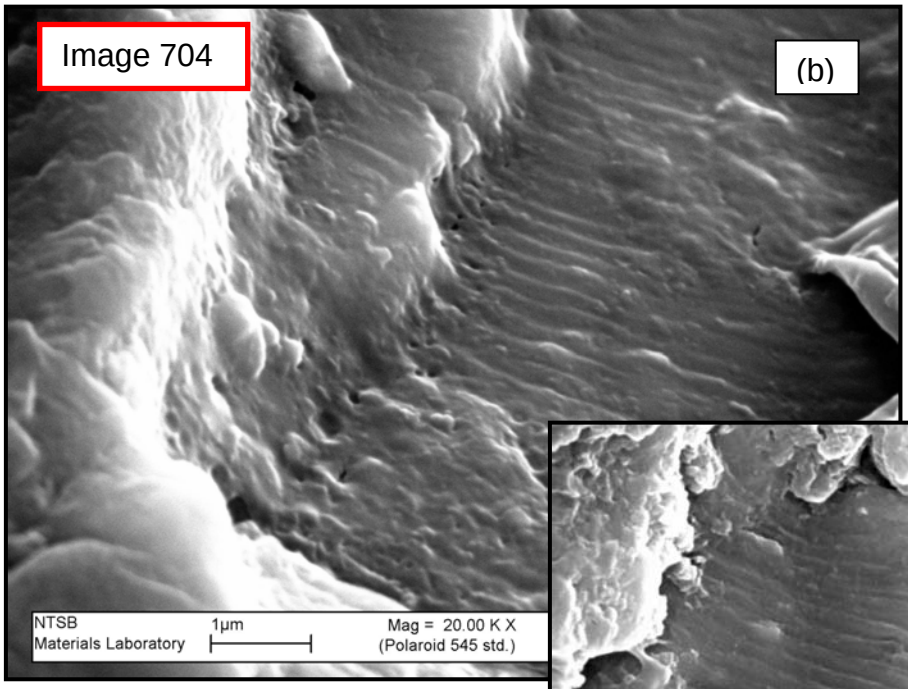


Striations



Fatigue and Overstress





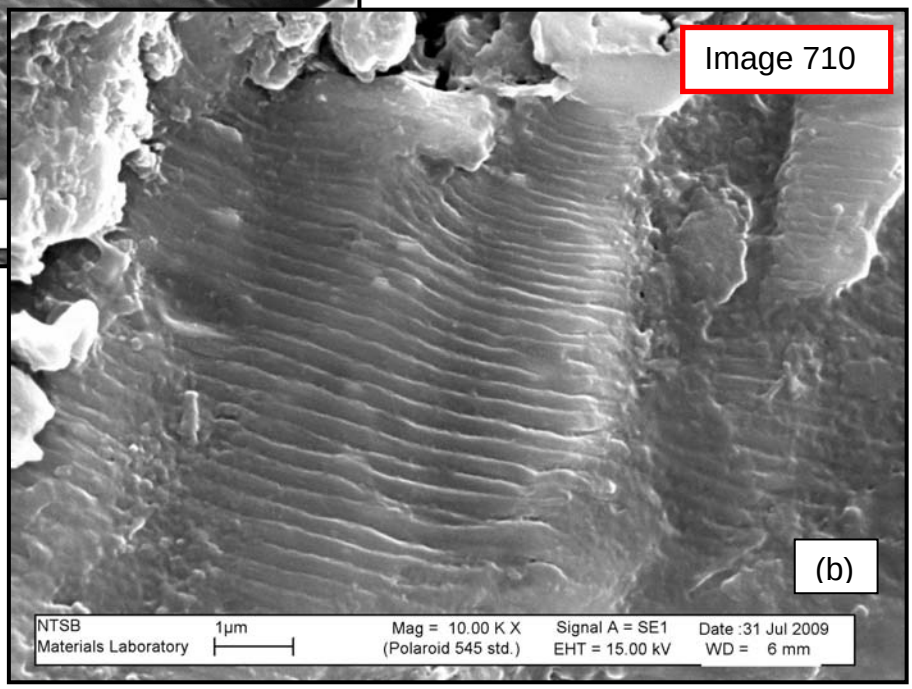


Figure 9—Example of striation count locations (a) at BS 836.2. Numbers identify images, see table D. Typical images of striations (b) and (c) used in the count.